



UNIVERSITI PUTRA MALAYSIA

EMULATION OF THE SPACE ROBOTICS SYSTEM ON EARTH

TEN SENG TEIK

ITMA 2001 5

EMULATION OF THE SPACE ROBOTICS SYSTEM ON EARTH

By

TEN SENG TEIK

**Thesis Submitted in Fulfilment of the Requirement for the
Degree of Master of Science in Institute of Advanced Technology
Universiti Putra Malaysia**

May 2001



TO MY DEAREST FATHER, MOTHER AND BROTHER

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Master of Science.

EMULATION OF THE SPACE ROBOTICS SYSTEM ON EARTH

By

TEN SENG TEIK

May 2001

Chairman: Dr. Md. Mahmud Hasan

Institute of Advanced Technology

Present and future, without the sophisticated and highly automated mechanisms, it is impossible to fulfil the humanity's destiny in space. Thus to determine the success of ambitious space missions of the future, the humans and space robots have to form an excellent integrated team. Generally space robotic systems are designed, developed and operated to assist or replace humans in accomplishing tasks that are dangerous, costly or simply impossible for humans. The nature and operation of space systems are totally different from on earth such as zero gravity environments, have made the modifications of design and usage of robotics in space very important. This research comprises an analytical and experimental study of space robot locomotion.

The main objective of this research work is to build a test-bed for space robot emulation that operates in the "zero gravity" situation. To experimentally study the locomotion of space robot in the laboratory, one has to create a "zero gravity" or "less gravity" environment. In order to perform simulations of partial or microgravity environments on earth requires some method of compensation for the earth's gravitational field. To

achieve this, gravity-less 2 Degrees-Of-Freedom robot with an unique instrumental arrangement was considered to compensate the gravity force.

The space robot kinematics and dynamics formulations are studied, especially the Denavit-Hartenberg (D-H) parameters and Newton-Euler formulation. The feedbacks of the robot's arms are detected by encoders at the servomotors and transducers around the robot and sent to the computer through PC interface card. The space robot dynamic algorithms were tested in simulation and as well as in practical. The data especially the torque values, the joint positions and angular velocities of the robot's arm in the "zero gravity" environment as well as with gravitational effect were taken from the experimental and simulation. The simulation comprises the combination of mechanical simulation and virtual prototyping software, Mechanical Desktop and MSC Working Model. The graphs were plotted from data by using Excel. The Mathematical software package, Mathematica is used to derive the equations of motion. Finally all the trend graphs were plotted using Excel. The results were compared and analyzed with derived equations to prove that the "zero gravity" condition is achieved. Moreover this instrumental setup for emulation of space robot system can be used for various algorithms study based on robotics, control and other areas.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

PENGIKUT JEJAK SISTEM ROBOTIK ANGKASA LEPAS ATAS BUMI

Oleh

TEN SENG TEIK

Mei 2001

Pengerusi: Dr. Md. Mahmud Hasan

Institut Teknologi Maju

Pada masa kini dan masa depan, cita-cita manusia dalam mengeksplorasi angkasa lepas tidak akan berjaya tanpa peralatan mekanisma automasi yang sangat canggih dan sofistikated. Oleh itu, manusia dan robot angkasa lepas perlu membentuk satu pasukan bersepadu yang sempurna untuk menentukan kejayaan dalam cita-cita misi angkasa lepas untuk masa hadapan. Secara amnya, sistem robot angkasa lepas direka, dibangun dan dioperasi untuk membantu dan mengganti manusia dalam melaksanakan kerja yang berbahaya, mahal atau mustahil bagi manusia. Sifat dan operasi bagi sistem angkasa lepas adalah jauh berbeza daripada di bumi kerana angkasa lepas mempunyai persekitaran tanpa graviti. Dengan itu, adalah sangat penting untuk mengubahsuai rekaan dan kegunaan robot dalam angkasa lepas. Penyelidikan ini merangkumi analisis dan eksperimentasi tentang gerakan robot angkasa lepas.

Objektif yang terpenting dalam penyelidikan ini ialah membina satu tapak ujian untuk pengikut jejak robot angkasa lepas yang beroperasi dalam keadaan tanpa graviti. Persekitaran tanpa graviti atau kurang graviti mesti diadakan untuk membuat

eksperimen tentang gerakan robot angkasa lepas dalam makmal di bumi. Cara-cara bagi mengimbangi graviti bumi diperlukan untuk menjalankan simulasi dengan persekitaran sebahagian atau mikrograviti atas bumi. Robot 2 *Degree-Of-Freedom* dengan cara pasangan peralatan yang unik dipertimbangkan untuk mengimbangi daya graviti seterusnya menjayakan penyelidikan ini.

Formula kinematik dan dinamik robot angkasa lepas dipelajari, terutamanya parameter Denavit-Hartenberg(D-H) dan formular Newton-Euler. Maklumbalas tangan robot yang dikesan oleh *encoder* di dalam *servomotor* dan *transducer* di sekeliling robot dihantar ke komputer melalui *PC interface card*. Algoritma robot angkasa lepas diuji dalam simulasi dan juga dalam praktikal. Data terutama nilai tork, kedudukan sambungan dan laju putaran tangan robot dalam keadaan tanpa graviti dan juga dengan graviti diperolehi daripada eksperimen dan program simulasi. Program simulasi terdiri daripada simulasi mekanikal dan perisian prototaip sebenar, *Mechanical Desktop* dan *MSC Working Model*. Perisian Matematik, *Mathematica* digunakan untuk mendapatkan persamaan. Akhir sekali, semua bentuk graf diperolehi dengan mengguna Excel. Keputusan dibandingkan dan dianalisis dengan persamaan untuk membuktikan keadaan tanpa graviti telah dicapai. Tambahan pula, persiapan peralatan untuk pengikut jejak sistem robot angkasa lepas ini boleh digunakan untuk pelbagai algoritma berasaskan robotik, kawalan dan bidang yang lain.

ACKNOWLEDGEMENTS

The author could not have accomplished this project without the help of God and a great many people. Thanks God that the author can complete his project successfully. First, the author would like to express his deep gratitude to his main project supervisor, Dr. Md. Mahmud Hasan, his supervisory committee, Assoc. Prof. Dr. Shamsuddin Sulaiman and Assoc. Prof. Dr. Waqar Asrar for the valuable advice, guidance and willingness to share their expertise.

The author also is indebted to the staffs of Faculty of Engineering and Institute of Advanced Technology, especially to Dr. Napsiah and Mr. Tajul Ariffin for providing the equipment, suggestions, and valuable aids to carry out this project and also the Graduate School of UPM and Ministry of Science, Technology and Environment for the great assistance and sponsorship.

The author would also like to acknowledge the help of Mr. Mah, Mr. Lee and other friends for their various ideas, suggestions and comments.

Special thanks to his dearest parents, Yut Sun and Peng Ean, his dearest brother, Seng Tatt , his dearest uncle Yut Meng and all his relative for their patience, encouragement and support.

Last but not least, the author appreciates the helps from the people around him through out the study.

I certify that an Examination Committee met on 28th May 2001 to conduct the final examination of Ten Seng Teik on his Master of Science thesis entitled “Emulation of the Space Robotics System on Earth” in accordance with Universiti Pertanian Malaysia (Higher Degree) Act 1980 and Universiti Pertanian Malaysia (Higher Degree) Regulation 1981. The Committee recommends that the candidate be awarded the relevant degree. Members of the Examination Committee are as follows:

NAPSIAH ISMAIL, Ph. D.
Faculty of Engineering,
Universiti Putra Malaysia.
(Chairperson)

MD. MAHMUD HASAN, Ph. D.
Institute of Advanced Technology,
Universiti Putra Malaysia.
(Member)

SHAMSUDDIN SULAIMAN, Ph. D.
Associate Professor,
Faculty of Engineering,
Universiti Putra Malaysia.
(Member)

WAQAR ASRAR, Ph. D.
Associate Professor,
Faculty of Engineering,
Universiti Putra Malaysia.
(Member)



MOHD. GHAZALI MOHAYIDIN, Ph.D.
Professor/Deputy Dean of Graduate School,
Universiti Putra Malaysia.

Date: 26 JUN 2001.

This thesis submitted to the Senate of Universiti Putra Malaysia has been accepted as fulfilment of the requirement for the degree of Master of Science.




AINI IDERIS, Ph.D.
Professor
Dean of Graduate School,
Universiti Putra Malaysia.

Date:

DECLARATION

I hereby declare that the thesis is based on my original work except for the quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UPM or other institutions.



TEN SENG TEIK

Date: 28th May 2001

TABLE OF CONTENTS

	Pages
DEDICATION	ii
ABSTRACT	iii
ABSTRAK	v
ACKNOWLEDGEMENTS	vii
APPROVAL SHEET	viii
DECLARATION FORM	x
LIST OF TABLE	xiv
LIST OF FIGURES	xv
LIST OF ABBREVIATION	xxvii
 CHAPTER	
1 INTRODUCTION	1
1.1 Introduction	1
1.2 Microgravity	4
1.3 Objectives	5
1.4 Organization of Thesis	6
 2 LITERATURE REVIEW	8
2.1 Definition of Robot	8
2.2 Space Robot	8
2.3 Microgravity Research Facilities	12
2.4 Simulation of space manipulators	15
2.5 Space Robotics Researches Regarding Microgravity Conducted in The Laboratory on Earth	16
2.6 Motions And Force Control	20
2.7 SCARA	21
2.8 Robot Arm Kinematics	22
2.8.1 The Direct Kinematics Problems	25
2.8.2 Links, Joints And Their Parameter	25
2.8.3 The Denavit-Hartenberg Representation	27
2.9 Robot Arm Dynamics	32
2.9.1 The Recursive Newton-Euler Formulation	35
2.9.2 Recursive Equations of Motion For Manipulators	39
2.9.3 Recursive Equations of Motion of A Link About Its Own Coordinate Frame	45
2.10 Drive Technologies	49
2.11 Brushless Servomotor Control	51
2.12 Conclusion	53



3	METHODOLOGY	54
3.1	Methodology	54
3.2	Experimental Module	55
3.3	The Equation Derivation Module	57
3.4	Simulation Module	58
3.5	Conclusion	59
4	DEVELOPMENTS OF TWO DEGREE OF FREEDOM SPACE ROBOT	60
4.1	Robot System Overview	60
4.2	Experiment Hardware	61
4.3	Mechanical Design	64
4.3.1	Air Bearing	64
4.3.2	Joints	68
4.3.3	Positive-Drive Belts	71
4.4	Electric and Electronic Design	72
4.4.1	Actuators	72
4.4.2	Measured Digital Positive and Derived Digital Velocity: Single Sensor	79
4.4.3	Encoder	80
4.4.4	Computer And Communication System	83
4.5	Simulation	84
4.6	Summary	86
5	DERIVATIONS OF THE EQUATIONS OF MOTION	89
5.1	Kinematics OF The Manipulator Structures	89
5.2	Dynamics Calculation	91
5.3	Conclusion	102
6	RESULTS AND DISCUSSIONS	103
6.1	Experimental Results	103
6.1.1	Results With Gravitational Effect	104
6.1.2	Results Without Gravitational Effect	114
6.1.3	Experimental Results Analysis And Discussions	122
6.2	Simulation Results	124
6.2.1	Simulation Results With Gravitational Effect	125
6.2.2	Simulation Results Without Gravitational Effect	132
6.2.3	Simulation Results Analysis And Discussions	143
6.3	Conclusion	146
7	CONCLUSION	147
7.1	Summary and Conclusion	147
7.2	Recommendation For The Future Research	153
	REFERENCES	154
	APPENDICES	158



LIST OF TABLE

Table	Page
2.1 Recursive Newton-Euler Equations of Motion	42
4.1 Robot arm system characteristics	80
5.1 Kinematics link parameters	83

LIST OF FIGURES

Figure	Page
2.1 Reduced-gravity aircraft	14
2.2 The direct and inverse kinematics problems	23
2.3 Link coordinate system and its parameters	30
2.4 Force and moments on link i	41
3.1 Flow chart of Methodology	56
4.1 2D SCARA experimental robot setup	62
4.2 Link 1 structure	63
4.3 Link 2 structure	63
4.4 Air bearing	65
4.5 Flexible coupling in link 1	69
4.6 Timing pulley with AC servomotor	69
4.7 Combination of the timing pulley and belt and the flexible moving shaft	70
4.8 Side view of flexible moving up down shaft in link 1	70
4.9 Teeth on the inside surface of the belt mesh with grooved pulley	71
4.10 Cross section of two servomotors: (a) standard DC (brush-type); (b) Brushless servomotor	73
4.11 Basic configuration of servo	75
4.12 6 switching transistor for 3 phase inverter circuit	77
4.13 Torque versus motor shaft angle θ for SM assuming a constant current in each of the three phases.	77
4.14 Coded disk from an incremental shaft encoder and three-ring incremental Shaft encoder	80



4.15	Typical output pattern for the CCW rotation of a three-ring in incremental encoder	82
4.16	The interface control panel window	84
4.17	MS Working Model simulation program	85
5.1	Establishing link coordinate system	90
5.2	Dynamics parameters	91
5.3	Mass distribution in the link	97
6.1	The front view of the set up of the robot's arm with gravitational effect	104
6.2	The side view of the set up of the robot's arm with gravitational effect	105
6.3	The Orientation profile of link 1 (experimental fast moving link 1 with the gravitational effect).	106
6.4	The angular velocity profile of link 1 (experimental fast moving link 1 with the gravitational effect)	106
6.5	The torque profile of joint 1(experimental fast moving link 1 with the gravitational effect)	107
6.6	The orientation profile of link 2 (experimental fast moving link 1 with the gravitational effect)	107
6.7	The torque profile of joint 2 (experimental fast moving link 1 with the gravitational effect)	107
6.8	The orientation profile of link 1 (experimental slow moving link 1 with the gravitational effect)	108
6.9	The angular velocity profile of link 1 (experimental slow moving link 1 with the gravitational effect)	108
6.10	The torque profile of joint 1 (experimental slow moving link 1 with the gravitational effect)	109
6.11	The orientation profile of link 2 (experimental slow moving link 1 with the gravitational effect)	109



6.12	The torque profile of joint 2 (experimental slow moving link 1 with the gravitational effect)	109
6.13	The orientation profile of link 2 (experimental fast moving link 2 with the gravitational effect)	110
6.14	The angular velocity profile of link 2 (experimental fast moving link 2 with the gravitational effect)	110
6.15	The torque profile of joint 2 (experimental fast moving link 2 with the gravitational effect)	111
6.16	The orientation profile of link 1 (experimental fast moving link 2 with the gravitational effect)	111
6.17	The torque profile of joint 1 (experimental fast moving link 2 with the gravitational effect)	111
6.18	The orientation profile of link 2 (experimental slow moving link 2 with the gravitational effect)	112
6.19	The angular velocity profile of link 2 (experimental fast moving link 2 with the gravitational effect)	112
6.20	The torque profile of joint 2 (experimental slow moving link 2 with the gravitational effect)	113
6.21	The orientation profile of link 1 (experimental fast moving link 2 with the gravitational effect)	113
6.22	The torque profile of joint 1 (experimental fast moving link 2 with the gravitational effect)	113
6.23	The orientation profile of link 1 (experimental fast moving link 1 without the gravitational effect)	114
6.24	The angular velocity profile of link 1 (experimental fast moving link 1 without the gravitational effect)	115
6.25	The torque profile of joint 1 (experimental fast moving link 1 without the gravitational effect)	115
6.26	The orientation profile of link 2 (experimental fast moving link 1 without the gravitational effect)	115

6.27	The torque profile of joint 2 (experimental fast moving link 1 without the gravitational effect)	116
6.28	The orientation profile of link 1 (experimental slow moving link 1 without the gravitational effect)	116
6.29	The angular velocity profile of link 1 (experimental slow moving link 1 without the gravitational effect)	117
6.30	The torque profile of joint 1 (experimental slow moving link 1 without the gravitational effect)	117
6.31	The orientation profile of link 2 (experimental slow moving link 1 without the gravitational effect)	117
6.32	The torque profile of joint 2 (experimental slow moving link 1 without the gravitational effect)	118
6.33	The orientation profile of link 2 (experimental fast moving link 2 without the gravitational effect)	118
6.34	The angular velocity profile of link 2 (experimental fast moving link 2 without the gravitational effect)	119
6.35	The torque profile of joint 2 (experimental fast moving link 2 without the gravitational effect)	119
6.36	The orientation profile of link 1 (experimental fast moving link 2 without the gravitational effect)	119
6.37	The torque profile of joint 1 (experimental fast moving link 2 without the gravitational effect)	120
6.38	The orientation profile of link 2 (experimental slow moving link 2 without the gravitational effect)	120
6.39	The angular velocity profile of link 2 (experimental slow moving link 2 without the gravitational effect)	121
6.40	The torque profile of joint 2 (experimental slow moving link 2 without the gravitational effect)	121
6.41	The orientation profile of link 1 (experimental slow moving link 2 without the gravitational effect)	121



6.42	The torque profile of joint 1 (experimental slow moving link 2 without the gravitational effect)	122
6.43	The orientation profile of link 1 (simulation fast moving link 1 without the gravitational effect)	125
6.44	The angular velocity profile of link 1 (simulation fast moving link 1 with the gravitational effect)	126
6.45	The torque profile of joint 1 (simulation fast moving link 1 with the gravitational effect)	126
6.46	The torque profile of joint 2 (simulation fast moving link 1 with the gravitational effect)	126
6.47	The orientation profile of link 1 (simulation slow moving link 1 with the gravitational effect)	127
6.48	The angular velocity profile of link 1 (simulation slow moving link 1 with the gravitational effect)	127
6.49	The torque profile of joint 1 (simulation slow moving link 1 with the gravitational effect)	128
6.50	The torque profile of joint 2 (simulation slow moving link 1 with the gravitational effect)	128
6.51	The orientation profile of link 2(simulation fast moving link 2 with the gravitational effect)	129
6.52	The angular velocity profile of link 2(simulation fast moving link 2 with the gravitational effect)	129
6.53	The torque profile of joint 2(simulation fast moving link 2 with the gravitational effect)	130
6.54	The torque profile of joint 1(simulation fast moving link 2 with the gravitational effect)	130
6.55	The orientation profile of link 2(simulation slow moving link 2 with the gravitational effect)	131
6.56	The angular velocity profile of link 2(simulation slow moving link 2 with the gravitational effect)	131



6.57	The torque profile of joint 2(simulation slow moving link 2 with the gravitational effect)	132
6.58	The torque profile of joint 1(simulation slow moving link 2 with the gravitational effect)	132
6.59	The orientation profile of link 1(simulation fast moving link 1 without the gravitational effect)	133
6.60	The angular velocity profile of link 1(simulation fast moving link 1 without the gravitational effect)	133
6.61	The torque profile of joint 1(simulation fast moving link 1 without the gravitational effect)	134
6.62	The torque profile of joint 2(simulation fast moving link 1 without the gravitational effect)	134
6.63	The orientation profile of link 1(simulation slow moving link 1 without the gravitational effect)	135
6.64	The angular velocity profile of link 1(simulation slow moving link 1 without the gravitational effect)	135
6.65	The torque profile of joint 1(simulation slow moving link 1 without the gravitational effect)	136
6.66	The torque profile of joint 2(simulation slow moving link 1 without the gravitational effect)	136
6.67	The orientation profile of link 2(simulation fast moving link 2 without the gravitational effect)	137
6.68	The angular velocity profile of link 2(simulation fast moving link 2 without the gravitational effect)	137
6.69	The torque profile of joint 2(simulation fast moving link 2 without the gravitational effect)	138
6.70	The torque profile of joint 1(simulation fast moving link 2 without the gravitational effect)	138
6.71	The orientation profile of link 2(simulation slow moving link 2 without the gravitational effect)	139

6.72	The angular velocity profile of link 2(simulation slow moving link 2 without the gravitational effect)	139
6.73	The torque profile of joint 2(simulation slow moving link 2 without the gravitational effect)	140
6.74	The torque profile of joint 1(simulation slow moving link 2 without the gravitational effect)	140
6.75	The orientation profile of link 1(simulation both links activated with link 2 moves faster without gravitational effect in different orientation)	141
6.76	The angular velocity profile of link 1(simulation both links activated with link 2 moves faster without gravitational effect in different orientation)	141
6.77	The torque profile of joint 1(simulation both links activated with link 2 moves faster without gravitational effect in different orientation)	142
6.78	The orientation profile of link 2(simulation both links activated with link 2 moves faster without gravitational effect in different orientation)	142
6.79	The angular velocity profile of link 2(simulation both links activated with link 2 moves faster without gravitational effect in different orientation)	142
6.80	The torque profile of joint 2(simulation both links activated with link 2 moves faster without gravitational effect in different orientation)	143
B1	Air Bearing	188
6.81	The orientation profile of link 1 (simulation both links activated with link 1 moves faster in different orientation with gravitational effect)	213
6.82	The angular velocity profile of link 1(simulation both links activated with link 1 moves faster in different orientation with gravitational effect)	213
6.83	The torque profile of joint 1(simulation both links activated with link 1 moves faster in different orientation with gravitational effect)	214
6.84	The orientation profile of link 2(simulation both links activated with link 1 moves faster in different orientation with gravitational effect)	214
6.85	The angular velocity profile of link 2(simulation both links activated with link 1 moves faster in different orientation with gravitational effect)	214
6.86	The torque profile of joint 2(simulation both links activated with link 1 moves faster in different orientation with gravitational effect)	215

6.87	The orientation profile of link 1(simulation both links activated with same maximum angular in different orientation velocity with gravitational effect)	215
6.88	The angular velocity profile of link 1(simulation both links activated with same maximum angular velocity in different orientation with gravitational effect)	216
6.89	The torque profile of joint 1(simulation both links activated with same maximum angular velocity in different orientation with gravitational effect)	216
6.90	The orientation profile of link 2(simulation both links activated with same maximum angular velocity in different orientation with gravitational effect)	216
6.91	The angular velocity profile of link 2(simulation both links activated with same maximum angular velocity in different orientation with gravitational effect)	217
6.92	The torque profile of joint 2(simulation both links activated with same maximum angular velocity in different orientation with gravitational effect)	217
6.93	The orientation profile of link 1(simulation both links activated with link 2 moves faster in different orientation with gravitational effect)	218
6.94	The angular velocity profile of link 1(simulation both links activated with link 2 moves faster in different orientation with gravitational effect)	218
6.95	The torque profile of joint 1(simulation both links activated with link 2 moves faster in different orientation with gravitational effect)	219
6.96	The orientation profile of link 2(simulation both links activated with link 2 moves faster in different orientation with gravitational effect)	219
6.97	The angular velocity profile of link 2(simulation both links activated with link 2 moves faster in different orientation with gravitational effect)	219
6.98	The torque profile of joint 2(simulation both links activated with link 2 moves faster in different orientation with gravitational effect)	220
6.99	The orientation profile of link 1(simulation both links activated with link 1 moves faster in same orientation with gravitational effect)	220
6.100	The angular velocity profile of link 1(simulation both links activated with link 1 moves faster in same orientation with gravitational effect)	221

6.101	The torque profile of joint 1(simulation both links activated with link 1 moves faster in same orientation with gravitational effect)	221
6.102	The orientation profile of link 2(simulation both links activated with link 1 moves faster in same orientation with gravitational effect)	221
6.103	The angular velocity profile of link 2(simulation both links activated with link 1 moves faster in same orientation with gravitational effect)	222
6.104	The torque profile of joint 2(simulation both links activated with link 1 moves faster in same orientation with gravitational effect)	222
6.105	The orientation profile of link 1(simulation both links activated with same maximum angular velocity in same orientation with gravitational effect)	223
6.106	The angular velocity profile of link 1(simulation both links activated with same maximum angular velocity in same orientation with gravitational effect)	223
6.107	The torque profile of joint 1(simulation both links activated with same maximum angular velocity in same orientation with gravitational effect)	224
6.108	The orientation profile of link 2(simulation both links activated with same maximum angular velocity in same orientation with gravitational effect)	224
6.109	The angular velocity of link 2(simulation both links activated with same maximum angular velocity in same orientation with gravitational effect)	224
6.110	The torque profile of joint 2(simulation both links activated with same maximum angular velocity in same orientation with gravitational effect)	225
6.111	The orientation profile of link 1(simulation both links activated with link 2 moves faster in same orientation with gravitational effect)	225
6.112	The angular velocity profile of link 1(simulation both links activated with link 2 moves faster in same orientation with gravitational effect)	226
6.113	The torque profile of joint 1(simulation both links activated with link 2 moves faster in same orientation with gravitational effect)	226
6.114	The orientation profile of link 2(simulation both links activated with link 2 moves faster in same orientation with gravitational effect)	226
6.115	The angular velocity profile of link 2(simulation both links activated with link 2 moves faster in same orientation with gravitational effect)	227

6.116	The torque profile of joint 2(simulation both links activated with link 2 moves faster in same orientation with gravitational effect)	227
6.117	The orientation profile of link 1(simulation both links activated with link 1 moves faster in different orientation without gravitational effect)	228
6.118	The angular velocity profile of link 1(simulation both links activated with link 1 moves faster in different orientation without gravitational effect)	228
6.119	The torque profile of joint 1(simulation both links activated with link 1 moves faster in different orientation without gravitational effect)	229
6.120	The orientation profile of link 2(simulation both links activated with link 1 moves faster in different orientation without gravitational effect)	229
6.121	The angular velocity profile of link 1(simulation both links activated with link 1 moves faster in different orientation without gravitational effect)	229
6.122	The torque profile of joint 2(simulation both links activated with link 1 moves faster in different orientation without gravitational effect)	230
6.123	The orientation profile of link 1(simulation both links activated with same maximum angular velocity in different orientation without gravitational effect)	230
6.124	The angular velocity profile of link 1(simulation both links activated with same maximum angular velocity in different orientation without gravitational effect)	231
6.125	The torque profile of joint 1(simulation both links activated with same maximum angular velocity in different orientation without gravitational effect)	231
6.126	The orientation profile of link 2(simulation both links activated with same maximum angular velocity in different orientation without gravitational effect)	231
6.127	The angular velocity profile of link 2(simulation both links activated with same maximum angular velocity in different orientation without gravitational effect)	232
6.128	The torque profile of joint 2(simulation both links activated with same maximum angular velocity in different orientation without gravitational effect)	232